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A WIDE-OPEN-WAVEGUIDE CAVITY FOR THE INTERNATIONAL LINEAR COLLIDER CRABBING SYSTEM*

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Abstract

The International Linear Collider (ILC) requires crabbing system to compensate 14 mrad crossing angle. The crabbing system at 1.3 GHz needs to provide 1.845 MV crabbing voltage for 250 GeV case and 7.4 MV for 1 TeV case and needs to be fitted within 3.8 m allocated space. In this paper, a Wide-Open-Waveguide (WOW) type cavity is proposed as one of the candidates due to its simple structure and reasonable High Order Mode (HOM) damping.

INTRODUCTION

The ILC crab cavity system is designed to provide crabbing in horizontal plane to compensate the crossing angle of 14 mrad towards head-on collision. The space allocated for crab cavity system is 3.8 m longitudinal (incorporating gate valves) and 0.1967±0.0266 m transverse, with its center 14.05 m away from the interaction point (IP) and a minimum 25 mm beampipe aperture, see Figure 1. This system will operate in CW mode at 2 K temperature and 1.3 GHz to provide 1.845 MV kick for 250GeV Center of Mass (CoM) (125 GeV beam energy) and 7.4 MV for 1 TeV CoM. It can also work at 2.6 or 3.9 GHz with lower kick voltage. The impedance budgets for this system are 48.8 MΩ/m horizontal and 61.7 MΩ/m vertical for 250 GeV case, both in circuit definition. For 1 TeV case, the impedance budgets are 195.2 MΩ/m horizontal and 246.8 MΩ/m vertical.

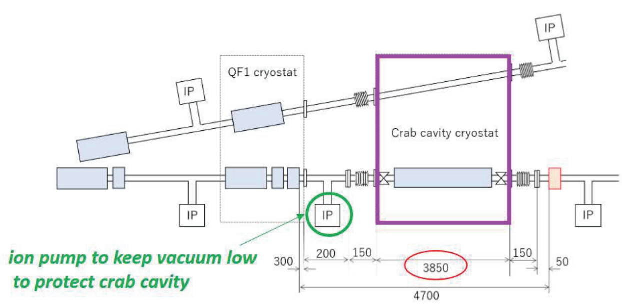

Figure 1: Space for the crab cavity system in ILC near IP [1].

WOW TYPE CAVITY DESIGN

In a WOW type cavity design, the fundamental mode is trapped in the cavity, Lower Order modes (LOMs) should not exist. All HOMs leak out through beampipe and get absorbed. It is possible to have multicell design in WOW type if the Same Order Modes (SOMs) are carefully treated. WOW type design is widely used in accelerating cavities, i.e., CESR-III single-cell cavity [2], KEK-B single-cell cavity [3], bERLinPro 7-cell cavity [4], and most recently, Electron Ion Collider (EIC) single-cell cavity [5]. For crab cavity, Fermi lab proposed a multicell design called Quasi-waveguide Multicell Resonator (QMiR) in 2014 [6] and CERN proposed single cell WOW type crab cavity for Large Hadron Collider (LHC) & Future Circular Collider (FCC) in 2015 [7], this is also where the name WOW came from. EIC also proposed to use WOW type RF-dipole (RFD) shape [8] crab cavity as a backup solution for 394MHz design, which however, cannot be directly scaled to 1.3GHz and fit into the space allocated for ILC thus further optimization is needed.

For LHC, both RFD and Double Quarter Wave (DQW) [9] designs are adopted, with the former for horizontal crabbing and the latter for vertical crabbing. For WOW type, it is natural to use RFD shape due to its simplicity of the joint design between cavity and beampipe. The same peak fields limitations as EIC crab cavity designs are used here, with 45 MV/m peak E field (E_{pk}) and 80 mT peak B field (B_{pk}). The bare cavity design, especially the shape of the capacitive poles, as well as the blending on the connections between capacitive poles and cavity body, is optimized towards a balance between E_{pk} and B_{pk}. 100mm inner diameter is chosen for the beampipe, with which the cutoff frequencies are at 1.758 GHz for TE_{11} mode and 2.297 GHz for TM_{01} mode, that allows propagation of the lowest frequency longitudinal and transverse modes, thus all monopole and dipole HOMs can propagate out.

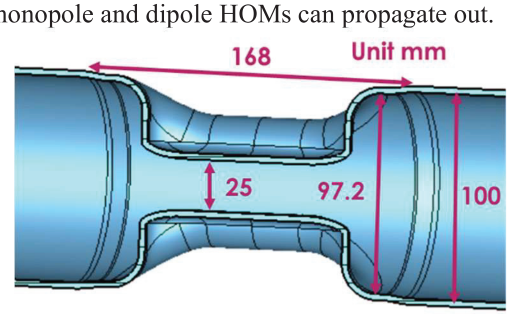

Figure 2: Geometry of the bare cavity.

The optimized cavity geometry is shown in Figure 2, with cavity parameter shown in Table 1. With this design the operating voltage could be 1.60 MV per cavity with 45 MV/m E_{pk} and 80 mT B_{pk}. 2 cavities will be used for 250 GeV case that can provide 3.2 MV crabbing voltage in total, 73.4% more than the requirement at 1.845 MV, and 5 cavities will be used for 1 TeV case that can provide 8.0 MV crabbing voltage in total, 8.1% more than the requirement at 7.4 MV.

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Table 1: Cavity Parameter

Property	Value
Operating frequency [GHz]	1.300
1st longitudinal HOM [GHz]	2.299
1st transverse HOM [GHz]	1.765
E_p/E_t with $E_t=V_t/(\lambda/2)$	3.24
B_p/E_t [mT/(MV/m)]	5.75
B_p/E_p [mT/(MV/m)]	1.77
G [Ω]	130.9
R/Q [Ω]	454.3
R_tR_s [Ω^2]	59446

The EIC specifications are used to help determine the length of the cavity. 1.48 MV nominal voltage (so that 5 cavities provide 7.4 MV in total for 1 TeV case) is used and field strengths are normalized to this voltage. Cavity helium vessel joints the cavity at 8 mT magnetic field level, length of helium vessel can be as short as 242 mm. Indium seal is placed at 2.5 mT, 168 mm from the cavity center, and Cu gasket is placed at 220 A/m (~0.28 mT), 257 mm from the cavity center. Indium seal can be used only if it is necessary, we choose not to use it in this design. Cu gaskets are used on both ends of the cavity, with cavity total length (flange to flange) at 514 mm. Figure 3 shows the locations of the interfaces.

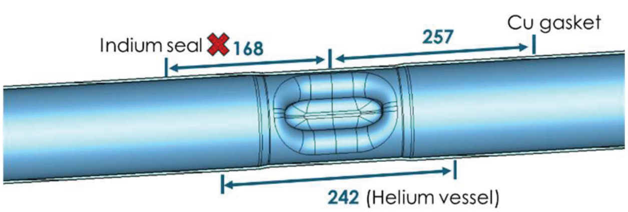

Figure 3: Locations of the cavity interfaces.

HOM DAMPER DESIGN

The major benefit of WOW type design is that the HOM damper is decoupled from the bare cavity design. It is outside the helium vessel thus simplifies the fabrication while comparing with LHC or EIC designs. The fundamental mode is attenuated to a level that is low enough on the HOM damper so that it is multipacting free. To fulfill the requirement on space allocation, two adjacent cavities share the damper unit in between, with two additional damper units on two ends. A variety of damper designs were considered, see Figure 4. Design A with Silicone Carbide (SiC) beamline absorber (BLA) was considered at the beginning but was quickly dropped majorly due to the change of specification on minimum aperture from 20 mm to 25 mm. With this change 5 WOW type cavities will be needed for 1 TeV case instead of 4, thus a more compact design is needed. Design B with Cu waveguide to coax damper was proposed in Down Selection Review on Crab Cavity Design meeting. Fundamental mode attenuates in the waveguide in transverse plane thus it can be compact longitudinally. Waveguide absorber is not considered here since waveguide absorbers require further R&D, especially for broadband, while coax absorbers are commercially available; waveguide absorbers are large and are complex/expensive while comparing with coax absorbers; mechanical support for waveguide absorber adds additional design complexity; and waveguide absorber can handle high power, while in ILC the average power is low. Similar debates happened in EIC 197MHz crab cavity [10] and waveguide to coax damper design is chosen for similar reasons.

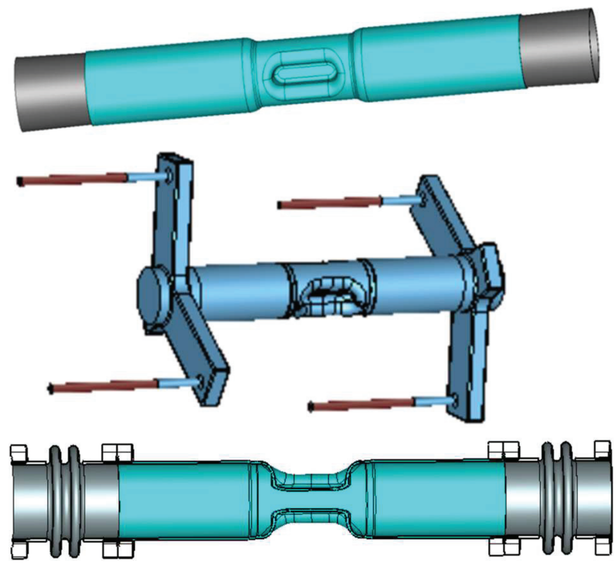

Figure 4: Damper unit designs from top to bottom: beamline absorber with SiC (design A); Cu waveguide to coax damper (design B); stainless steel bellow as HOM damper (design C).

During the down selection review meeting, design B was criticized due to its nature of high current application while ILC is low current machine. Inspired by the QMiR design that proposed to use stainless steel as HOM absorber, design C is proposed to use stainless steel bellows to damp the HOMs in the homework session of the review meeting. For fundamental mode this design is multi single-cell cavities that are separated by stainless steel bellows in between. Since HOMs propagate along the beampipe, for HOMs this design is one multi-cell cavity with both superconducting Nb and normal conducting stainless steel as cavity wall, with same order HOMs strongly coupled thus well separated in frequency domain, thus their impedances do not overlap.

The HOM power is low in the crab cavity since it is a mA range pulsed machine, with worst case considered to be 8.75 mA beam current, 10 Hz RF repetition rate and 961 μs bunch train length. The longitudinal loss factor of this design is 2.71 V/pC up to 8 GHz. Modes higher than 8 GHz propagates outside the cryomodule with 25 mm beampipe connecting to adjacent components. HOM power in this design is estimated to be less than 1 W per cavity, power handling of 1 W per damper would be sufficient.

Fundamental power dissipation on damper unit is also a concern, the setup shown in Figure 5, with results shown in Table 2. In this table we listed the results of one cavity only, as shown in the Figure, as well as the case with two adjacent cavities sharing one bellow in between.

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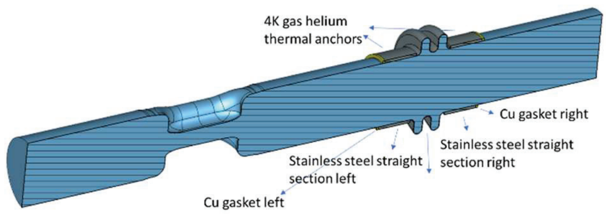

Figure 5: Setup for fundamental power dissipation study.

Table 2: Fundamental Power Dissipation on the Damper Components [W]

	As shown in the Figure	**Two adjacent cavities sharing one bellow**
Cu gasket left	0.13	0.13
Stainless steel straight section left	2.13	2.38
Stainless steel corrugated section	0.02	0.04
Stainless steel straight section right	0.25	2.38
Cu gasket right	1e-4	0.13

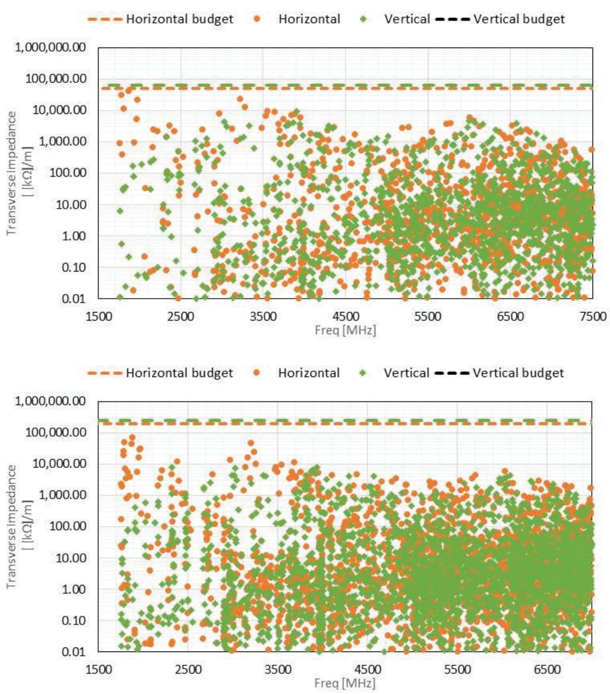

Figure 6: Transverse impedance spectrum with budget lines for 250 GeV case (top) and 1 TeV case (bottom).

With 1 W HOM power per cavity, bellows between cavities bear with 1 W HOM power dissipation each and bellows on the ends bear with 0.5 W each. The total power including both fundamental and HOMs would be 2.9 W each for the end bellows, and 5.8 W each for the center bellows. For 1 TeV case with 5 cavities and 6 bellows, the total power on the stainless steel components would be 29 W, which is absorbed by 4 K gas helium.

In this design two corrugations are used in the bellow to maximize the length of the straight section for HOM damping. It is suggested by R. Rimmer that two corrugations can be further apart to provide more displacement transversely, while longitudinally they are the same.

Impedance spectrum of string assembly for 250 GeV case and 1 TeV case were studied, with ends of the string capped using 100 mm to 25 mm ID reducer. The results are shown in Figure 6, both meet the impedance budgets. In case further margin is needed for the 250 GeV case, simulations showed that HOMs with high impedances can be suppressed with additional stainless steel spool pieces between cavities and/or on the ends.

Multipacting simulations were done on both bare cavity and HOM damper designs B and C, as we expected, there is no multipacting in HOM damper designs and bare cavity behaves similarly to the LHC and EIC RFD without end-groups.

MECHANICAL CONSIDERATIONS

Due to limited resources, no detailed mechanical designs were done. It is suggested to use LHC RFD type scissor jack tuner that applies force symmetrically in vertical direction to the top and bottom of the cavity. Simulation shows that the bare cavity with 3 mm thick Nb produces a maximum 28 MPa stress under 2.2 atm external pressure at room temperature. At 2 K, with 2.5 kN force on each side, the maximum stress on the bare cavity is 0.24 GPa with 0.12 mm displacement on each side. With a 10.2 MHz/mm tuning sensitivity, the tuning range is 2.5 MHz. For 180 kHz tuning requirement, 370 N force with 18 µm displacement would suffice. The pressure sensitivity is 725 Hz/mBar for bare cavity and 308 MHz/mBar with tuner fixed. The Lorentz force detuning is -1.51 kHz/MV^2, which is -3.31 kHz for 1.48 MV, which can be compensated by the tuner. Helium vessel would help stiffen the cavity towards better mechanical performance. Figure 7 shows the cryomodule with 5 WOW cavities with 6 bellows. It can be fitted into 3.8 m space and bellows on the ends also serve as thermal transition between 2 K and room temperature. Tuner and helium vessel are shown on the left most cavity.

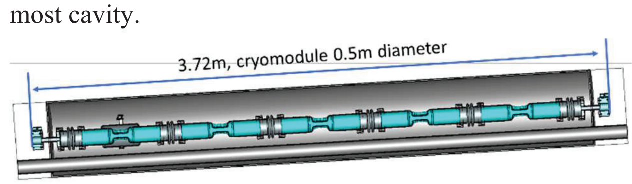

Figure 7: Cryomodule string assembly.

SUMMARY

WOW type crab cavity was designed for ILC, with stainless steel bellows to damp the HOMs. Each cavity provides 1.60 MV crabbing voltage, with 2 cavities for 250 GeV case and 5 cavities for 1 TeV. Impedance spectrum for both cases were calculated to meet the budgets. Detailed Multiphysics simulations including RF, multipacting, thermal and mechanical showed promising results.

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